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Perspective

Microbial Fuel Cells as a Promising Power Supply for Implantable Medical Devices

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Abstract: The Future of Energy is focused on the consolidation of new energy technologies. Among them, Fuel Cells (FCs) are on the Energy Agenda due to their potential to reduce the demand for fossil fuel and greenhouse gas emissions, their higher efficiency (as fuel cells do not use combustion, their efficiency is not linked to their maximum operating temperature) and simplicity and absence of moving parts. Additionally, low-power FCs have been identified as the target technology to replace conventional batteries in portable applications, which can have recreational, professional, and military purposes. More recently, low-power FCs have also been identified as an alternative to conventional batteries for medical devices and have been used in the medical field both in implantable devices and as micro-power sources. The most used power supply for implantable medical devices (IMD) is lithium batteries. However, despite its higher lifetime, this is far from enough to meet the patient's needs since these batteries are replaced through surgeries. Based on the close synergetic connection between humans and microorganisms, microbial fuel cells (MFCs) were targeted as the replacement technology for batteries in IMD since they can convert the chemical energy from molecules presented in a living organism into electrical energy. Therefore, MFCs offer the following advantages over lithium batteries: they do not need to be replaced, avoiding subjecting IMD users to different surgeries and decreasing medical costs; they do not need external recharging as they operate as long as the fuel is supplied, by the body fluids; they are a more environmentally friendly technology, decreasing the carbon dioxide and other greenhouse gases emissions resulting from the utilization of fossil fuels and the dependency on fossil fuels and common batteries. However, they are complex systems involving electrochemical reactions, mass and charge transfer, and microorganisms, which affect their power outputs. Additionally, to achieve the desired levels of energy density needed for real applications, an MFC system must overcome some challenges, such as high costs and low power outputs and lifetime.

Keywords: microbial fuel cells (MFCs); implantable medical devices (IMD); challenges; microscale; power output

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1. Background

A medical device is considered implantable if it is partly or totally introduced into the human body, rebuilding its functions towards a better quality of life and/or increasing the longevity of its users. Implanted medical devices (IMD) are devices intended to aid or deliver the functions of malfunctioning organs, such as pacemakers, cochlear implants, drug pumps, blood counters, and blood glucose meters. As they maintain the health and the life quality of their users, they are a powerful weapon in healthcare. It was reported that 8–10% of the American population and 5–6% of people in industrialized countries have IMD [1]. According to the American Stroke Association, 60,000 pacemakers are implanted each year in the United States [2] and the European Society of Cardiology revealed that only in 2016, 590 pacemakers were implanted per million of the population [3]. Additionally, as the population and its life expectancy average age continue increasing, maintaining the health and quality of life of this aging population presents new demands for healthcare services.

The common feature among the different IMD is that they require a stable and efficient power supply, with energy consumption at a level of micro to milliwatt, depending on the size and location of the IMD. For example, the power requirements for a pacemaker are between 30 µW to 100 µW, for a drug pump, 100 µW to 2 mW, and for a cochlear implant 5 mW to 10 mW [4]. Additionally, due to their running time and the locality where they are used, they should have a long-running lifetime, a low self-discharging rate, high reliability, and biocompatibility with the human body. Currently, the most used power supply for IMD is lithium batteries due to their high energy densities and safe performance. However, although its lifetime is up to 10 years, this is far from enough to meet the patient's needs since IMD are replaced through surgeries. This process subjects the patients to different surgeries, causing great pain and leading to high medical costs. Furthermore, its potential toxicity and size limit its application in IMD. The volume occupied by a battery in an implantable pacemaker is 75% of the whole pacemaker, and as the power requirements of the IMD increase, the battery volume also increases, leading to a system medically unacceptable [5]. Therefore, finding a way to provide energy for IMD in a highly safe, efficient, and continuous way is mandatory, as the technologies currently used to power them have a lower lifetime. As a result, the IMD has to be replaced with some frequency through different surgeries; for example, the pacemakers have to be replaced due to battery problems within 5–8 years. Knowing that the human body contains or releases many forms of energy, such as heat, the chemical energy of organic molecules, and physical forms of energy, such as breathing and motion, using devices that can convert these physical and chemical energies into electrical energy can be the solution to IMDs [4–7].

Low-power fuel cells (LpFCs) are on the Energy Agenda due to their potential to replace conventional batteries in small applications, either for recreational, professional or medical purposes [8,9]. Among them, biological fuel cells (BFCs), which can produce electrical energy using glucose and oxygen, which are abundant in the blood, exhibit a power output on the milliwatt level, mild operation conditions, simple structure, excellent biocompatibility and long lifetime are suitable to power the majority of the IMDs. Therefore, using these systems to power IMDs will largely reduce the medical costs and the surgeries needed to replace the batteries, increasing the life quality of the IMDs users [4–7,9–15]. Current research on BFCs used in IMDs is mainly concentrated on employing microorganisms to oxidize the fuel substrates (MFCs) or enzymes (enzymatic fuel cells, EFCs) [4–7,9–15]. EFCs employ enzymes as catalysts showing excellent compatibility and considerable power but suffer from the short duration of the enzyme and incomplete oxidation of the substrate, leading to low conversion efficiency and rapid degradation of the cell performance [16].

There are different reviews in the literature regarding the BFCs systems and their application in IMDs that can be very useful to those who want to go deeper in understanding and further developing this technology [4–7,9–16]. This work is focused on the MFCs technology and its main challenges, stressing its great potential for application in IMDs.

2. Microbial Fuel Cells for IMDs

Microbial fuel cells (MFCs) have been studied and developed to produce electricity from organic matter using microorganisms as biocatalysts since 1911 (Figure 1), being Michael Cresse Potter the first to perform work on this subject [17]. Potter discovered that electrical energy was produced when *Escherichia coli* species degraded organic compounds.

Microbial fuel cells are similar to any other type of fuel cell, having two electrodes (anode and cathode) usually separated by a proton exchange membrane (PEM). The main difference is that they use organic substrates as fuels and electrochemically active microorganisms as a catalyst to produce electricity.

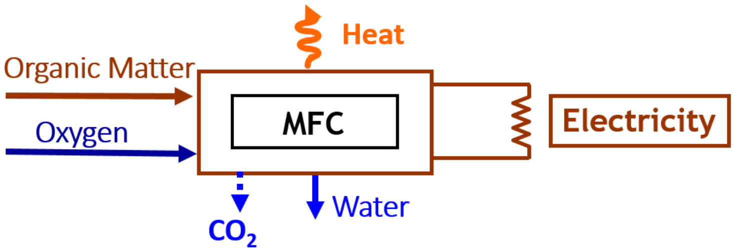

Figure 1. Schematic representation of a microbial fuel cell.

Considering the close symbiotic relationship between humans and microorganisms, MFCs emerge as a continuous, long-life, and safe power source for IMD, as they are able to convert the chemical energy from molecules presented in a living organism into electrical energy at temperatures close to the body temperature, avoiding additional procedures, such as enzyme separation and purification, and the reproduction of the bacterial cells leads to a biocatalyst regeneration offering a long-term stability and fuel efficiency, but suffer from low power outputs [18–20]. Therefore, the main difference between MFCs and lithium batteries is that as the concentration of the reactants is continually re-established by the body fluids, the MFCs do not need external recharging or replacement and, theoretically, will operate as long as there is a constant fuel supply.

Microbial fuel cells were the first FC applied in the medical field and are a more attractive and promising technology for IMD since the abundant availability of different substrates, such as glucose and oxygen in the blood, allows continuous production of electricity [21–25]. Based on that, microscale MFCs (microMFCs) have gained much attention over the past decade [26–31], but their relatively low power density and durability, and higher costs still remain the main bottlenecks for their practical application [26–28].

Sun et al. [21] used human white blood cells at the anode side of a microbial fuel cell to study the ability of these systems to power neural implants. The cathode was fed with ferricyanide in a phosphate-buffered saline solution. The results show that despite the lower currents achieved, the MFC could be able to power neural implants. Chiao et al. [22] produced a US patent for a miniaturized microbial fuel cell that produces energy from glucose or other metabolite(s) from the body fluids, allowing a long-term power source for IMDs. Were used microfabrication techniques to reduce the cell size and costs and electrodes that favour the electron transport and power production. Siu and Mu [23] developed a microfabricated polydimethylsiloxane (PDMS) microbial fuel cell (MFC) with micropillar electrodes to increase energy production. This cell is characterized by a flexible and biocompatible structure towards its use in the body to power IMDs. The results showed that using a single droplet of human plasma of 15-µL, containing 4.2 mM blood glucose, the cell produced a maximum power density of 401.2 nW/cm^2. When operated for 60 min, the cell showed an average power density of 42.4 nW/cm^2 and a coulombic efficiency between 9% and 14.7%. Han et al. [24] developed an MFC inoculated with simulated intestinal fluid to be implantable in the transverse colon. The environmental features of the transverse colon were simulated, adjusting the dissolved oxygen and the pH. The cell allowed a stable power output after two months of operation with a maximum power density of 73.3 mW/m^2. Further studies on the internal cell resistance and power density showed that the MFC could generate a power output between 7 mW to 10 mW according to the size of the intestinal surface area, which is enough to power an IMD. Dong et al. [25] also developed an MFC to be implemented in the human transverse colon, considering the colon environment. The cell proposed was a single-chamber MFC without a membrane, which allowed a stable operation, but the parameters of the simulated colonic environment, such as the pH and the oxidation-reduction potential, changed with the operation time. Therefore, the maximum power output achieved, 1.6 mW, was not enough for some IMDs. Mardanpour and Yahmaei [29] proposed a microfluidic microbial fuel cell with a nickel electrode to promote biofilm growth, improving the power output, and reducing the electrode costs, using *Escherichia coli*, a non-photogenic species usually found in the lower intestine, as biocatalyst. It studied the viability of using the proposed cell to power an IMD using glucose and urea as substrates in respectively the human blood and urine. The microfluidic MFC feed with glucose allows for achieving a maximum power output of 5.2 $\mu W/cm^2$ and with urine 14 W/m^3. Yoon et al. [30] proposed a PDMS-based membraneless microfluidic MFC with a parylene C coating to lower the oxygen permeability, one of the main bottlenecks in the development of microscale MFCs and a micropillar-structured Au electrode to reduce the internal resistance of the cell. The proposed cell achieved a maximum power density of 182.0 ± 4.82 $\mu A/cm^2$, being a promising system to power IMDs. Mousavi et al. [31] developed a microfluidic microbial fuel cell using a nanostructure nickel-based material as an anode electrode and *Escherichia coli* as a biocatalyst towards an enhancement of the electrode surface area and an increase the cell power output. The proposed cell achieved a maximum power output of 343 W/m^3.

Towards its application in IMDs, the MFCs need to have a reduced size, simpler design, and low weight, use non-photogenic species as biocatalysts and biofuels, such as urine and blood, which contain organic substrates, that are used as fuel [21–25,29–31].

3. Microbial Fuel Cells for IMDs Challenges and Perspectives

As summarized, microscale MFCs have received considerable attention from the scientific community owing to their application in IMDs. However, the maximum power output achieved has not been up to the level where they can be commercialized since it is mandatory to achieve higher power outputs within a limited electrode surface area and restricted size. Therefore, towards its commercialization and massive use, the microMFCsmust overcome the following key challenges:

(1) Low power outputs

The ideal performance of an MFC depends on the electrochemical reactions occurring between the organic matter and the final acceptor, usually oxygen. The real potential is always lower than the ideal one due to three irreversible losses: Activation, Ohmic, and concentration. The activation losses are dominant at low current densities and are due to the sluggish kinetics of the electrochemical reactions occurring on both the anode and cathode sides. Phenomena involving adsorption/desorption of reactant species, transfer of electrons, and the nature of the electrode surface contribute to this loss. At intermediate currents, the predominant loss is the Ohmic loss and is due to the transport resistance of ions on the electrolyte and electrons through the electrodes. At high currents, the major loss is concentration loss and is due to the inability to maintain the initial substrate concentration in the bulk fluid and to mass transport limitations. To achieve a higher performance/power output, it is mandatory to reduce these losses [18–20].

Activation losses can be reduced using microorganisms that are able to transfer electrons directly to the electrode, the so-called "electricigens." Furthermore, these species have the ability to completely oxidize the organic substrates and develop biofilms at the anode electrode. The biofilm matrix is composed of three essential components: water, extracellular polymeric substances (EPS), and bacteria. The EPS immobilizes the bacterial cells by attaching themselves permanently using cell adhesion molecules as biofilm matrix and allowing direct electron transfer. Due to the presence of a high cell density, a greater potential for cell-to-cell contact is possible in biofilms helping to stimulate the electron transfer mechanism and allowing a considerable conversion capacity, and thus an enhancement on the electricity production. Since the extracellular electron transfer takes place at the anode between the electrode surface and the biofilm, the anode can be considered one of the critical components of the microscale system. Therefore, a well-developed biofilm is vital to obtain increased efficiencies with an MFC. Considering that the anode compartment in microMFCs is small, this limited space may constrain the development of a suitable biofilm. Hence, the anode electrode selection is crucial in terms of surface area and electron transfer rate between the electrode surface and the biofilm. The anode electrode can be fabricated using tailor-made microstructures to increase the electrode's surface area and provide favorable conditions for microbial growth, biofilm development, and electron transfer. Nickel and Nickel based electrodes have been used as stable and low-cost electrodes due to their high specific surface area, allowing a faster electrochemical reaction and a higher electrochemical performance [29,31]. Gold electrodes are also used due to their biocompatibility, high conductivity, and compatibility with conventional microfabrication techniques [23,26,27,30]. However, these electrodes have a higher cost and a higher internal resistance due to a high contact resistance at the interface between the microorganism and the electrode [26,27]

The ohmic losses can be reduced by shortening the distance between the electrodes, increasing the ionic conductivity of the electrolytes, and reducing the internal resistance of the system, using membrane-less configurations [18–20,25,30]. These losses can also be reduced by improving the flow pattern of the electrolyte by modifying the cell design in order to prevent the catholyte/oxygen crossover [30].

(2) Biocompatibility

As these systems are implantable in the human body, it is mandatory to use materials with higher stability and non-toxic, teratogenic, carcinogenic, nor antigenic, limiting drastically the materials that can be used for microfabrication. These limitations should be applied to both the material itself and its degradation products. Additionally, due to a limited available surface area for biofilm formation and small system size, the microMFC needs to ensure proper biofilm development and electron transfer. Therefore, fabricating the microMFC using biocompatible materials and a high surface area to volume ratio to lower de electrolyte resistance and electrodes with a high surface area is another significant challenge. These electrodes not only increase the available surface area for biofilm development but also improve the extracellular electron transfer efficiency and the diffusion rates of metabolic by-products [27]. Bioelectrodes of conventional microMFCs are made of Platinum, Carbon, Nickel, or Gold [23–25,29–31]. The use of platinum as an electrode leads to high power outputs, but these electrodes are very expensive and have low durability due to poisoning by contaminants [32]. As mentioned, microMFCs suffer from high internal resistances, motivating the use of carbon-based materials, which provide a very small internal resistance, as electrodes. However, due to their non-uniform structure, most of them are not fully compatible with microfabrication being, and for this reason unsuitable for microscale MFCs [26–28].

Polydimethylsiloxane (PDMS) is a low-cost, biocompatible, and flexible silicone-based material with a simple fabrication method that has been used as a structural material in microMFCs [23,30]. However, has a high oxygen permeability that may decrease the cell efficiency. Based on that, another biocompatible material often used, which showed improved performances due to its low oxygen permeability, is the polymethyl-methacrylate (PMMA) [29,31].

(3) High cost

For the implementation of an MFC in the market and to be competitive with the actual technologies, it is mandatory to decrease its costs and increase its power output and durability. MFCs have a high capital cost, increasing the costs of the IMD, due to the use of membranes to physically separate the anode and the cathode, and platinum catalysts, to promote the oxygen reduction reaction, which is very expensive and have low durability. Therefore, using electrodes with good biocompatibility, stable performance, as well as low cost, is mandatory [23,26,27,29–31].

(4) Low durability/lifetime

Degradation is another important challenge to overcome in fuel cells technology and is primarily due to delamination of the catalyst layer and agglomeration of the catalyst particles, which lead to a loss of the electrochemically active surface area of the catalyst and catalyst and membrane degradation [32]. Although the loss of efficiency is unavoidable, the degradation rate can be minimized through an understanding of the degradation and failure mechanisms and through the use of more stable and higher corrosion resistance materials.

Towards its use in IMDs, a microMFC needs stable and constant reactants supply in order to maintain the required power output. Once used in IMDs, a microMFC will suffer from the accumulation of proteins, cells, or other biomaterials on the electrode's surface, blocking the access of the substrate, glucose, and the oxidant, oxygen, to the electrode's surface, deteriorating the cell performance. Furthermore, biofouling also affects the membrane, decreasing the protons transfer and increasing the cell's internal resistance, lowering the cell performance and their long-term operation ability. As biofouling is unavoidable, the design of a microMFC needs to consider the cumulative nature of these materials to minimize the biofouling problems [4,5].

4. Summary

There is a need for new power supplies so the IMD can assist in such mass healthcare applications, as the technologies currently used to power them have a lower lifetime.

MFCs are a promising sustainable technology to meet the energy needs of IMD since the fuel and the oxidant needed for their operation can be directly harnessed from their surroundings, offsetting the medical costs and the surgeries needed to replace/recharge them. Additionally, these systems have higher biocompatibility and autonomy, simpler design, and moderate operating conditions.

The electricity generation in an MFC is accomplished by microbial catabolism, electron transfer from microbes to the anode, reduction in electron acceptors at the cathode, and proton transfer from the anode to the cathode, and all these processes influence the MFC performance. Towards its use in IMD, there has been a growing amount of work on microMFCs in the last years, both on the microbiological issues and on the engineering ones, which managed to increase its power outputs. However, they still have higher costs and power outputs and durability below the desirable since the performance of this type of fuel cell is affected by limitations based on irreversible reactions and processes occurring in the cell.

As the microMFCs will be used in the human body, due to toxicity issues, it is important to use non-pathogenic microorganisms that are able to produce and transfer electrons directly to the anode electrode. To this end, it is crucial to use microorganisms that form biofilms at the electrode surface for enhanced power outputs.

As the anode electrode layout has a clear effect on the biofilm formed at its surface and consequently on the electrons transfer rate and energy production by the MFC, there is a need for new materials and designs that favor the biofilm adhesion at the anode electrode and promote a faster electron transfer towards an enhancement of the anode performance and consequently the cell performance.

Among the different costs associated with this technology, the major percentage of the total cost is the cathode catalyst due to the use of platinum, which is a noble metal and so very expensive, to promote the oxygen reduction reaction. Therefore, the strategy is to use more active catalysts, especially platinum-free ones, to enhance their morphology and structure.

The second major contribution to the overall cost is related to the membrane used to separate the anode and the cathode. Therefore, it is important to use materials with an increased proton transfer from the anode to the cathode while minimizing the risks of unwanted species transfer from the cathode to the anode, with lower costs.

As the loss of efficiency and biofouling during the long-term operation are unavoidable, the design of the cell needs to consider the cumulative nature of proteins, cells, or other biomaterials, and it is mandatory to use more stable materials with higher durability.

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References

1. Joung, Y.-H. Development of implantable medical devices: From an engineering perspective. *Int. Neurourol. J.* **2013**, *17*, 98–106. [CrossRef] [PubMed]
2. Gupta, N.; Kiley, M.L.; Anthony, F.; Young, C.; Brar, S.; Kwaku, K. Multi-center, community-based cardiac implantable electronic devices registry: Population, device utilization, and outcomes. *J. Am. Heart Assoc.* **2016**, *5*, e002798. [CrossRef]
3. Raatikainen, M.J.; Arnar, D.O.; Merkely, B.; Camm, A.J.; Hindricks, G. Access to and clinical use of cardiac implantable electronic devices and interventional electrophysiological procedures in the European Society of Cardiology Countries, 2016 report from the European Heart Rhythm Association. *Europace* **2016**, *18*, 1–79. [CrossRef] [PubMed]
4. Amar, A.B.; Kouki, A.B.; Cao, H. Power Approaches for Implantable Medical Devices. *Sensors* **2015**, *15*, 28889–28914. [CrossRef] [PubMed]
5. Zebda, A.; Alcaraz, J.-P.; Vadgama, P.; Shleev, S.; Minteer, S.D.; Boucher, F.; Cinquin, P.; Martin, D.K. Challenges for successful implantation of biofuel cells. *Bioelectrochemistry* **2018**, *124*, 57–72. [CrossRef]
6. Orhan, S. Power Sources for implantable medical devices. *Device Technol. Appl. Electron.* **2002**, *18*, 76–79.
7. Wang, Y.; Wang, H.; Xuan, J.; Leung, D.Y.C. Powering future body sensor network systems: A review of power sources. *Biosens. Bioelectron.* **2020**, *166*, 112410. [CrossRef]
8. Xu, Q.; Zhang, F.; Xu, L.; Leung, P.; Yang, C.; Li, H. The applications and prospect of fuel cells in medical field: A review. *Renew. Sust. Energy Rev.* **2017**, *67*, 574–580. [CrossRef]
9. Vilas Boas, J.; Oliveira, V.B.; Pinto, A.M.F.R.; Simões, M. Fuel Cell Bioreactors. In *Comprehensive Biotechnology*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 464–478.
10. Rasouli, M.; Phee, L.S.J. Energy sources and their development for application in medical devices. *Expert Rev. Med. Devic.* **2010**, *7*, 693–709. [CrossRef]
11. Nishaa, V.; Soumya; Spoorthi, B.V.; Desai, V.S.; Meda, U.S. Powering Implantable Medical Devices with Biological Fuel Cells. *ECS Trans.* **2022**, *107*, 19197–19215.
12. Singh, R.; Kaur, N.; Singh, M. Bio-compatible bio-fuel cells for medical devices. *Mater. Today-Proc.* **2021**, *44*, 242–249. [CrossRef]
13. Ibrahim, R.; Shaari, N.; Aman, A.H.M. Bio-fuel cell for medical device energy system: A Review. *Int. J. Energy Res.* **2021**, *45*, 14245–14273. [CrossRef]
14. Wu, H.; Zhang, Y.; Kjøniksen, A.-L.; Zhou, X.; Zhou, X. Wearable Biofuel Cells: Advances from Fabrication to Application. *Adv. Funct. Mater.* **2021**, *31*, 2103976. [CrossRef]
15. Justin, G.A.; Zhang, Y.; Cui, X.T.; Bradberry, C.W.; Sun, M.; Sclabassi, R.J. A metabolic biofuel cell: Conversion of human leukocyte metabolic activity to electrical currents. *J. Biol. Eng.* **2011**, *5*, 5–9. [CrossRef]
16. Zhang, J.L.; Wang, Y.H.; Huang, K.; Huang, K.J.; Jiang, H.; Wang, X.M. Enzyme-based biofuel cells for biosensors and in vivo power supply. *Nano Energy* **2021**, *84*, 105853. [CrossRef]
17. Potter, M.C. Electrical Effects Accompanying the Decomposition of Organic Compounds. *Proc. R. Soc. B* **1911**, *84*, 260–276.
18. Oliveira, V.B.; Simões, M.; Melo, L.F.; Pinto, A.M.F.R. Overview on the developments of microbial fuel cells. *Biochem. Eng. J.* **2013**, *73*, 53–64. [CrossRef]
19. Kumar, S.S.; Kumar, V.; Kumar, R.; Malyan, S.K.; Pugazhendhi, A. Microbial fuel cells as a sustainable platform technology for bioenergy, biosensing, environmental monitoring, and other low power device applications. *Fuel* **2019**, *255*, 115682. [CrossRef]
20. Vilas Boas, J.; Oliveira, V.B.; Simões, M.; Pinto, A.M.F.R. Review on microbial fuel cells applications, developments and costs. *J. Environ. Manag.* **2022**, *307*, 114525. [CrossRef]
21. Sun, M.; Justin, G.A.; Roche, P.A.; Zhao, J.Z.J.; Wessel, B.L.; Zhang, Y.Z.Y.; Sclabassi, R.J. Passing data and supplying power to neural implants. *IEEE Eng. Med. Biol.* **2006**, *25*, 39–46.
22. Chiao, M.; Lin, L.; Lam, K.-B. Implantable, Miniaturized Microbial Fuel Cell. U.S. Patent US7,160,637B2, 9 January 2007.
23. Siu, C.-P.-B.; Mu, C. A Microfabricated PDMS Microbial Fuel Cell. *J. Microelectromech. Syst.* **2008**, *17*, 1329–1341. [CrossRef]
24. Han, Y.; Yu, C.; Liu, H. A microbial fuel cell as power supply for implantable medical devices. *Biosens. Bioelectron.* **2010**, *25*, 2156–2160. [CrossRef] [PubMed]
25. Dong, K.; Jia, B.; Yu, C.; Dong, W.; Du, F.; Liu, H. Microbial fuel cell as power supply for implantable medical devices: A novel configuration design for simulating colonic environment. *Biosens. Bioelectron.* **2013**, *41*, 916–919. [CrossRef] [PubMed]
26. Ren, H.; Lee, H.S.; Chae, J. Miniaturizing microbial fuel cells for potential portable power sources: Promises and challenges. *Microfluid. Nanofluid.* **2012**, *13*, 353–381. [CrossRef]
27. Choi, S. Microscale microbial fuel cells: Advances and challenges. *Biosens. Bioelectron.* **2015**, *69*, 8–25. [CrossRef] [PubMed]
28. Parkhey, P.; Sahu, R. Microfluidic microbial fuel cells: Recent advancements and future prospects. *Int. J. Hydrogen Energy* **2021**, *46*, 3105–3123. [CrossRef]
29. Mardanpour, M.M.; Yaghmaei, S. Characterization of a microfluidic microbial fuel cell as a power generator based on a nickel electrode. *Biosens. Bioelectron.* **2016**, *79*, 327–333. [CrossRef] [PubMed]

30. Yoon, J.Y.; Ahn, Y.; Schröder, U. Parylene C-coated PDMS-based microfluidic microbial fuel cells with low oxygen permeability. *J. Power Sources* **2018**, *398*, 209–214. [CrossRef]
31. Mousavi, M.R.; Ghasemi, S.; Sanaee, Z.; Nejad, Z.G.; Mardanpour, M.M.; Yaghmaei, S.; Ghorbanzadeh, M. Improvement of the microfluidic microbial fuel cell using a nickel nanostructured electrode and microchannel modifications. *J. Power Sources* **2019**, *437*, 226891. [CrossRef]
32. Pinto, A.M.F.R.; Oliveira, V.B.; Falcão, D.S. *Direct Alcohol Fuel Cells for Portable Applications: Fundamentals, Engineering and Advances*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2018; ISBN 978-0-12-811849-8.

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